# State-of-the-Art Review of Aquifer Thermal Energy Storage Systems for Heating and Cooling Buildings

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## ABSTRACT

Aquifer Thermal Energy Storage (ATES) systems have been designed, installed and operated for over 25 years. Hundreds of large-scale ATES systems have been realized. Optimization techniques in utilizing a combination of natural sources of heat and cold and multiple demands in buildings are discussed. Specifically designs are reviewed, which utilize an aquifer as a seasonal store in conjunction with or without heat pumps, cooling towers, dry coolers, and HX in fresh air intake as sources of cold in the winter months and then used for building cooling during the warm months. Storing waste heat or heat in the summer months and used for heating buildings in the cold months either directly or with heat pumps and/or use of waste heat from cooling buildings in the summer is also presented. Hybrid systems are reviewed, which often provide base load building demand and smaller traditional HVAC systems for peaking demand.

## 1. Background

Underground Thermal Energy Storage (UTES) and specifically Aquifer Thermal Energy Storage (ATES) have moved from a demonstration stage to a well established and documented technology over the last thirty years. The major application of ATES is storing thermal energy (whether heat or “cold”) seasonally for use in heating and cooling buildings. However, applications to industry and greenhouses are increasing.

The first demonstration/pilot projects were installed in the early 1980s in the US, China, Switzerland, and Denmark. The international Energy Agency’s (IEA) Implementing Agreement on Energy Conservation through Energy Storage (ECES) supported several Annexes (work groups) on UTES commencing in the early 1980s. For several reasons cold storage for cooling buildings with “cold” stored in the winter proved the most promising in temperate and northern climates: The natural underground temperature is typically only 0 to 10 $^{o}$C warmer than the required storage temperature for cooling of buildings while in the case of hot storage it is 40 to 80 $^{o}$C colder than the required temperature for heating, resulting in much larger thermal losses in the latter case. Also there are scaling and mineralization problems with hot storage which are less prevalent in cold storage. In order for wells in unconsolidated formations to remain viable over a long period of time the design and operation must ensure that fines and precipitation do not clog pores resulting in short lifetime of wells or increased maintenance costs to keep wells operating efficiently. In addition the cost of wells should be partially offset by cost avoidance of mechanical equipment to make these projects financially viable. In the case of rock aquifers, the challenge is ensuring that the formation has sufficient small fractures and fissures to properly store thermal energy. The following figure shows the economy of scale for aquifer systems in the Netherlands (cost level 2002).

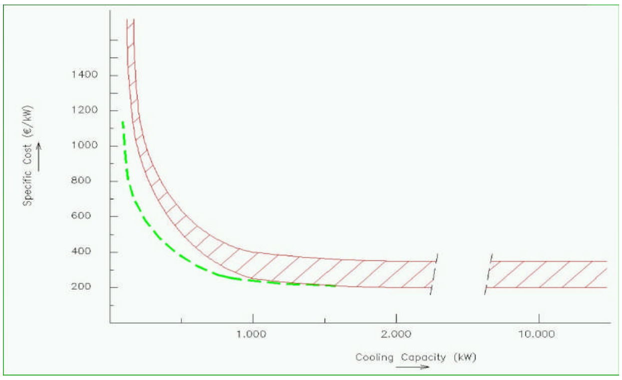

Figure 1. Scale of Economy for ATES systems indicating a breakpoint at about 500 kWt (~150 tons)

## 2. Geology and Well Design

Aquifers that can be utilized for ATES are limited to deposits of sands and gravels and highly fractured rock, preferably within about 150 m (500 ft) to surface. Water quality further limits useful aquifers to those with consistent concentrations of dissolved oxygen, limited mineral content, and relatively high porosity and hydraulic conductivity. These conditions make ATES less universally applicable than borehole thermal energy storage (BTES), which can be applied in almost all geological formations. If the geology is correct there are many advantages of ATES compared to BTES. In the case of ATES water is the vehicle to move thermal energy into and out of the storage medium (sand/gravel/highly fractured rock) directly, while in BTES the thermal energy is conducted into the storage medium (sand/gravel/soil/rock) through distances of about 5m. In addition, it is difficult to get thermal energy into and out of a borehole system with high thermal power, while in an aquifer system water can be pumped at a high rate. The net result is that it is often possible to utilize the stored thermal energy in an ATES system directly for cooling or heating while in a BTES system it is more difficult and usually requires a heat pump to deliver the appropriate temperatures. Those factors affecting ATES design are:

- Stratigraphy
- Grain size distribution
- Structures and fracture distribution
- Aquifer depth and geometry
- Storage coefficient
- Permeability
- Leakage factor confining layers
- Degree of consolidation
- Thermal gradient
- Static head
- Natural ground water flow
- Direction of flow
- Water chemistry

Table 1.  Major criteria for unconsolidated aquifer

| **Aspect** | **Lower limit** | **Typical** | **Upper limit** |
|---|---|---|---|
| Aquifer thickness (m) | 2-5 | 25 | None (partial use) |
| Aquifer depth (mbgs) | 5 (injection pressure) | 50 | 150 (economic) |
| Aquifer permeability (m/s) | 3 10exp-5 | 3 10exp-4 | 1 10exp-3 |
| Groundwater flow (m/d) | 0 | 0.1 | 0.3 |
| Static head (mbgs) | 50 | 10 | -5 |

Well construction in an unconsolidated formation requires reverse rotary drilling to create a controlled borehole diameter, get good quality ground samples, and to reduce the need for bentonite in the drilling fluid.  This is necessary to prevent clogging of pores in the formation which would lead to high back pressures.  Rock drilling also requires care to prevent closing off of the fractures.  In unconsolidated formations a thick gravel pack surrounds the screen which is carefully located in vertical formations that have good hydraulic conductivity (i.e., very low concentrations of silt and/or clay).  The basic design criterion is to keep the flow velocity of the injection water low enough for fines to collect in the gravel pack.  Thus wells can be back-flushed readily at the end of each season to maintain low injection resistance.  This ensures the longevity of the wells as well as reducing pumping energy.

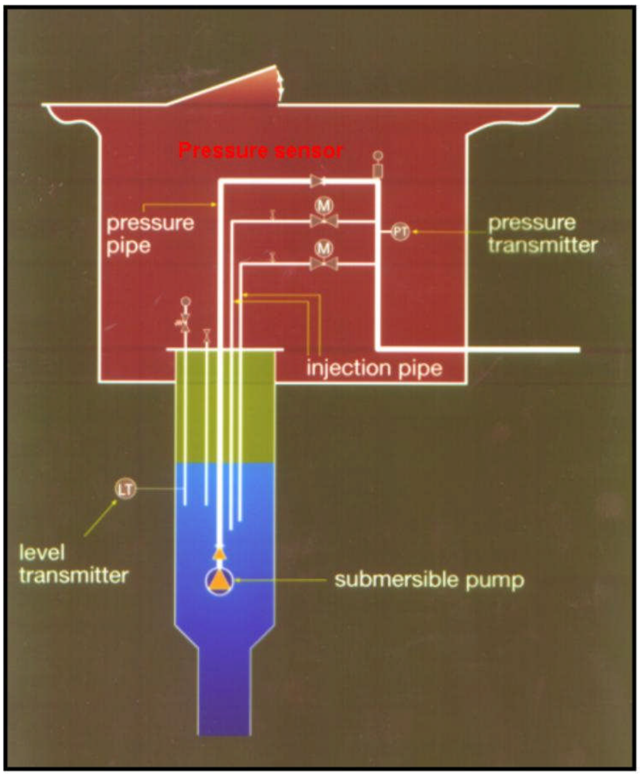

Figure 2.  Well piping scheme of extraction/ injection well for unconsolidated formation

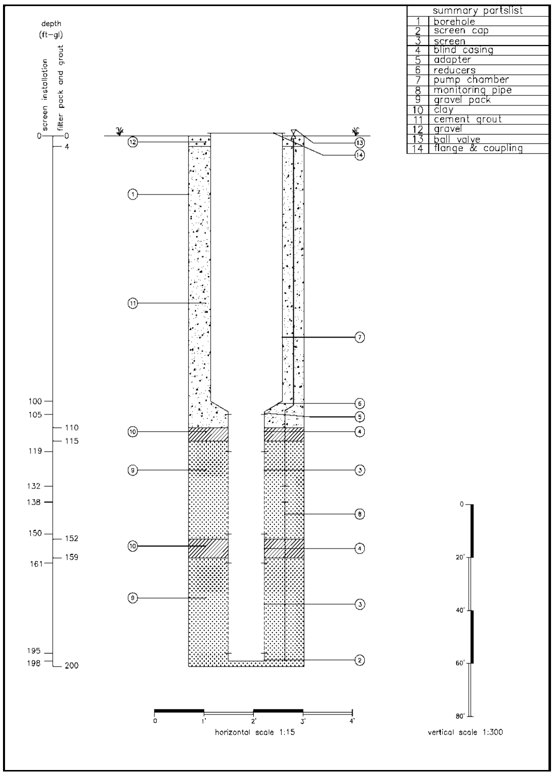

Figure 3. Cross section for extraction/injection well for unconsolidated formations

Variable speed pumps are used to match load conditions during extraction and to ensure water is sufficiently chilled during storage. This could potentially create a problem during low flow conditions. If pressures drop in any portion of the water column from supply to injection wells, out-gasing of the groundwater and entrance of oxygen into the system can occur. This could result in metal oxides forming, creating a possible long term problem with clogging of formation pores. To reduce this likelihood, a downhole pressure maintaining valve or multiple injection pipes are placed within the well with shut-off valves maintaining a minimum pressure in the transit lines. These design criteria result in much larger diameter wells that would normally be expected for a standard water extraction water supply well.

## 3. Modeling

This requires the use of hydrogeologic software such as CONFLOW or HST3/2D. In order to model the aquifer and storage, aquifer testing is required. This may require one large well and two monitoring wells. The aquifer hydraulic gradient, transmissivity and porosity are obtained from these tests. Models utilized in the design process are:

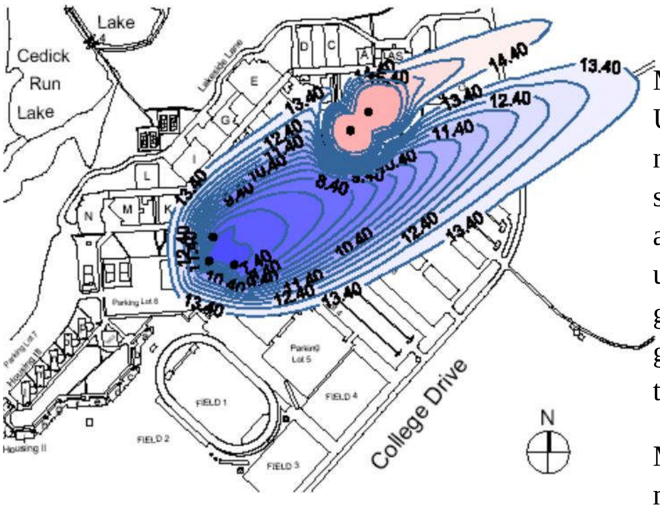

Figure 4: Modeling of aquifer temperature distributions after 20 years of operation.

MLPU (an acronym of Multi Layer Program Unsteady state) is an analytical groundwater model. The model can be used for modeling steady state and transient groundwater flow at a local or sub-regional scale. It can also be used for optimization of well field lay-out given data on groundwater heads or groundwater head changes (e.g. pumping tests).

MicroFEM is a finite-element program for multiple-aquifer steady-state and transient groundwater flow modeling.

HST2D/3D is a finite difference computer model for the simulation of heat and solute transport in saturated porous media. The model is based on the original HST3D model developed by the USGS and modified by Verbeek Consultant for IF Technology bv.

CONFLOW is a thermal front tracking model developed by Lund Group of Ground Heat (1995). It simulates a two-dimensional groundwater flow and the motion of the thermal fronts in an aquifer layer. The main assumptions are that aquifer layer has constant thickness and is a homogeneous, porous medium. The interactive computer model displays the flow pattern and the thermal fronts graphically.

## 4. System Design

The basic elements of an ATES system are the source of thermal energy, the delivery system, the aquifer store, and the thermal loads.

*Thermal Loads:* The most common application of ATES is cooling buildings. Even in more northern climates most large buildings are cooling load dominated. With very well designed (green) buildings becoming more common, the reduced heating demand is more substantial than the reduced cooling demand due to interior gains, making the imbalance even greater. Another reduced cooling demand due to interior gains, making the imbalance even greater. Another common application is heating of buildings. If both heating and cooling are required, systems can be designed for optimal efficiency. Within the building sector the most common applications are buildings with long hours of operation such as hospitals, academic buildings, shopping malls, hotels, multiple family housing, and office buildings which have a high level of utilization. Less common applications are greenhouses and industrial heating and cooling. While small buildings and single family housing might benefit, the problem is that storage volume may be too low resulting in too high a loss factor of seasonal stored energy. In practice at least a thermal demand of 200 kWt (~50 tons) is the smallest that can be matched with seasonal thermal storage. More recently thermal utilities which provide thermal energy to small buildings as part of a small district heating/cooling system are expanding the use of seasonal thermal storage.

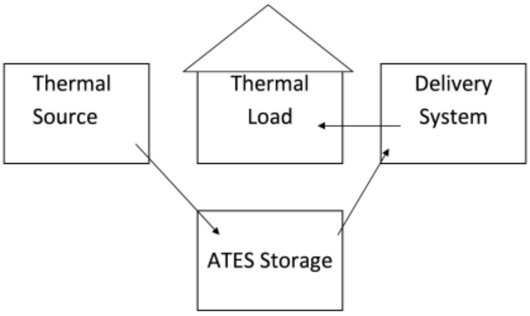

Figure 5: Basic Elements of ATES

Table 2. Thermal Source of Cold with Typical Temperatures (source side)

| Cold Source | EWT | LWT |
|---|---|---|
| Cooling tower | 15 | 6 |
| Dry cooler | 15 | 7 |
| Fresh air HEX | 15 | 8 |
| Water body | 15 | 6 |
| Heat pump/chiller | 15 | 6 |

*Thermal Cold Source:* The most common thermal source is cold outside air in Winter. It is collected by a cooling tower, dry cooler, and/or heat exchanger from fresh air intake on a building. Also common is waste cold water from a heat pump (while generating heat). Less common is cold water from a harbor, ocean, estuary, river or lake. If chilled water is being stored, for most applications it is optimum to store as cold as possible for direct use. In practice the minimum is ~5 $^{o}$C (41 $^{o}$F). Any lower temperature might result in freezing water.

*Thermal Heat Source:* The source of heat is most commonly waste heat from heat pumps which are being used to cool in summer months. Less common is waste heat from cogenerators or industrial processes. Another heat source is solar thermal collected in the summer months. Direct application is not as easily achieved since high temperatures are required by the delivery system. In these cases additional traditional sources are required to boast the temperature such as boilers and heat pumps.

*Delivery System:* The most effective and efficient HVAC system for ATES is one which separately handles latent and sensible loads during the cooling season. Fresh air intakes for most climates produce a substantial latent cooling load. To effectively reduce the wet bulb temperature of incoming outside air the coolant needs to be below 12 $^{o}$C (54 $^{o}$F). To realize the required wet bulb temperature and utilize the stored thermal energy effectively, a larger heat exchanger than normally applied in the the air handling unit is required with a counterflow configuration. A second HEX can utilize the warm water for reheat when needed. This typically results in a discharge temperature of aquifer water at 18 $^{o}$C (65 $^{o}$F).

In any event an air-to-air heat recovery system with both latent and sensible heat recovery reduces the fresh air thermal demand and is typically included in the ATES delivery system design. The sensible heat and cooling demand is often delivered by a radiant system or fan coil. Radiant ceilings are becoming more popular in these cases. In the case that the ATES system serves both for heating and cooling the HVAC system often includes heat pumps. In this case the cooling load is often delivered directly with the heat pump for short peak periods when the ATES system can’t provide the full load.

*ATES store:* The entire system including the ATES store needs to supply not only the thermal energy for the year but also the peak thermal power. The later criterion cannot always be cost justified. An optimum ATES system can supply the vast majority of thermal energy demand utilizing the ATES store when designed to serve as a thermal base load thermal plant.

The most important aspect of the design of wells is to ensure that surrounding properties are not adversely affected by the ATES store. A careful configuration of wells is required to ensure that the hydraulic head does not extend substantially onto adjacent properties. (E.g., delta hydraulic head no more than 30 cm (1 ft) at the property boundary.) Another requirement is that the temperature change would not reduce the possibility of a neighboring property owner utilizing ATES. (E.g., delta temperature change not larger than 0.5 $^{o}$C (1 $^{o}$F) at the boundary.) Finally, it is critical that there is not a thermal breakthrough between warm (hot) and cold stores in the long run (e.g. over a twenty year period). To achieve these conditions requires a very sophisticated and careful modeling. Figures 5 and 6 below show an example of three well configurations with one well configuration impact extending thermally beyond the property boundaries and the other two, more intertwined configurations, staying within the boundary.

The simplest system for ATES cold seasonal thermal storage utilizes a cooling tower (or dry cooler) during the winter months to charge cold wells. The cold aquifer store is then used to directly cool a building or buildings in the summer. Such a system requires a peaking chiller to supply cold when the ATES system is not adequate. An example is the recently completed Richard Stockton College project. Here an existing chilled water loop system connects five university buildings including a multi-purpose recreation building, two academic buildings, a small sports gymnasium, and a performing arts center.

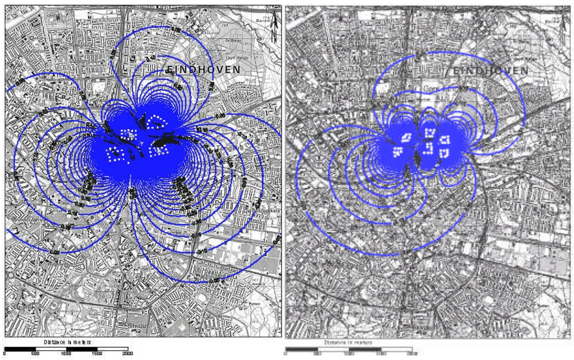

Figure 6. Two well configurations showing impact

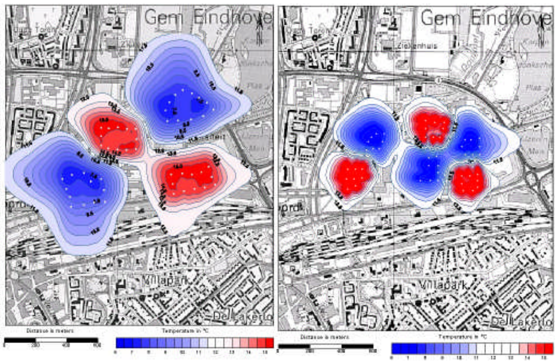

Figure 7. The same well configurations showing hydraulic thermal influence after twenty years of operation

The existing chillers on four building serve as “peakers”. Two of the buildings have a low but constant demand with occasional large thermal peak demands during special events. The ATES system is designed to handle the base load of these five buildings and the chillers serve to answer the special events demands.

*Optimum Systems:* An example of an optimum system is one that delivers heat during the winter at the same time generating cold water as a byproduct. Thus no extra energy is utilized to generate this chilled water.

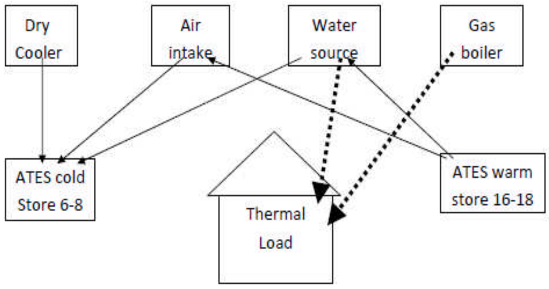

Figure 8. Winter operation of optimum ATES system

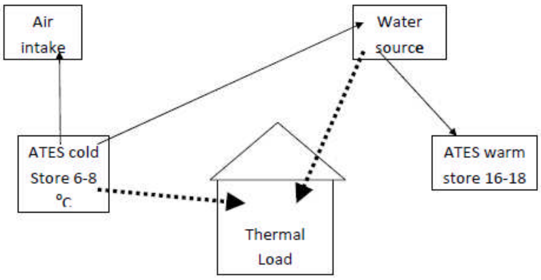

Figure 9. Summer operation of optimum ATES system

In the winter the water source heat pump utilizes 18 °C (65 °F) water stored in the summer operating at a relative high efficiency, delivering the base load heating for the building. In addition, when the outside temperature is below 0 °C, warm ATES water is utilized to preheat incoming fresh air and at the same time the cold water from an eventual dry cooler is stored in the ATES cold wells. When the heating demand cannot be fully supplied by the heat pump then a gas boiler comes on as a “peaker”. The amount of gas energy is typically less than

10% of total energy demand while about 50 % of peak thermal demand. The dry cooler is utilized to make additional cold water when air temperature is below 2 $^{o}$C.

In the summer operation the base load cooling is supplied directly by the ATES cold wells to both the building including the fresh air intake. When the cooling load cannot be met by the ATES cold wells the heat pump comes on as a “peaker”. Again the ATES cold wells supply the vast majority of the cooling load.

The system is designed to optimize, financially, by trading off peak load from the ATES system with traditional sources for short periods of time - reducing up-front investment with conventional peakers.

## 5. Some ATES project examples

*Institutional building example*

The ATES/HP system applied at the Klina Hospital in Brasschaat, Belgium, is an example of the abovementioned optimized system. Since 2000, the ATES/HP system provides both heating and cooling for the 440 bed hospital. The major part of the cooling and a smaller part of the heating is provided directly by the aquifer store. A three year monitoring program shows that the ATES/HP cooling capacity is about 1.2 MW and that about 75% of the annual cooling demand is provided directly, i.e. without running the heat pump as a chiller Desmedt et al, 2007). The saving of primary energy of the ATES/HP system as compared to a conventional gas boiler and electrical chiller system has been about 65%.

*Agricultural Example*

ATES system has been utilized for the first time in heating and cooling of a 360 $m^2$ greenhouse in Mediterranean climate in Adana, Turkey (Turgut et al., 2008). The basic concept of the ATES system utilizes the greenhouse as “solar collector” to store heat in summer and ambient air when temperature is less than 10ºC to store cold in winter. With “zero” fossil fuel consumption leading to 68% energy conservation, 20-40% increase in product yield depending on season and simple payback time of about 1 year, the ATES system shows a high potential for greenhouse climatisation.

*Industrial example*

The Wavin site in Hardenberg, the Netherlands, is an industrial site with a dozen plastics factories. Since 1996 the process cooling is provided by an aquifer system with a cooling capacity of about 5.0 MW. The maximum groundwater flow rate of 480 $m^3/h$ is produced from 6 abstraction wells and reinjected via 6 infiltration wells. This is a “cooling only”application. The aquifer system is thermally balanced by charging cold groundwater during the winter months. The cold is originating from surface water and cooling towers.

*District/ Cogeneration examples*

The Reichstag complex in Berlin, Germany has a bio-fueled co-generator that produces electricity. Waste heat is used in the winter directly to heat buildings and in the summer to drive an absorption chiller. When excess heat is generated (Fall and Spring) it is stored in a rock aquifer. When excess "cold" is generated by the absorption chiller (in Summer) it is stored in another aquifer. The aquifer temperatures retrieved are not as high grade as directly generated. Therefore, the system has a hot and warm supply and a cool and cold supply. The temperature demands of the loads are separated for these four temperature loops.

Another hot ATES storage system is tied to a cogeneration plant in Neubrandenburg, Germany. Here excess heat from a 90 MWt plant at 90 $^{o}$C is stored in a porous sandstone rock aquifer below 1200m deep. A "cold" well is located 1300 m distance from the warm well. The warm well delivers 12 MWt at 80 $^{o}$C (F. Kabus et al, 2006)

ATES is linked to a district cooling system that serves the inner city of Stockholm with natural cold from a lake (Värtan). The surface water is produced from a depth of 35 m and has a temperature ranging from +4 to +6 $^{o}$C. A heat pump system can lower the supply temperature to +3$^{o}$C if required. The designed capacity with the surface water is 60 MW. The purpose with the Aquifer Storage is to increase the capacity in order to connect more customers to the system. This is achieved by short- term storage where cold from the lake is stored during night and recovered during peak hours at daytime. The system is designed for a capacity of approx. 25 MW cooling power at a storage working temperature of +4 to +14oC and at a flow rate of 600 l/s. cold is produced for 20-25 Euro/MWh excluding the capital and labor costs, while the market value for cold is about 100 Euro/MWh (Andersson, 2007).

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